Extreme Fast Charging (XFC) Gap Assessment

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Overview

Timeline

- Project Start Date: July 2016
- Project End Date: May 2017

Budget

- Total Funding: $775k
- FY 2016: $775k
  - ANL: $300k
  - INL: $250k
  - NREL: $225k
- FY 2017: $0

Barriers

- Cost – System costs are higher than non-fast charge capable models
- Performance – Fast charge is more challenging for energy dense cells
- Life – Fast charge can impact cell cycle life

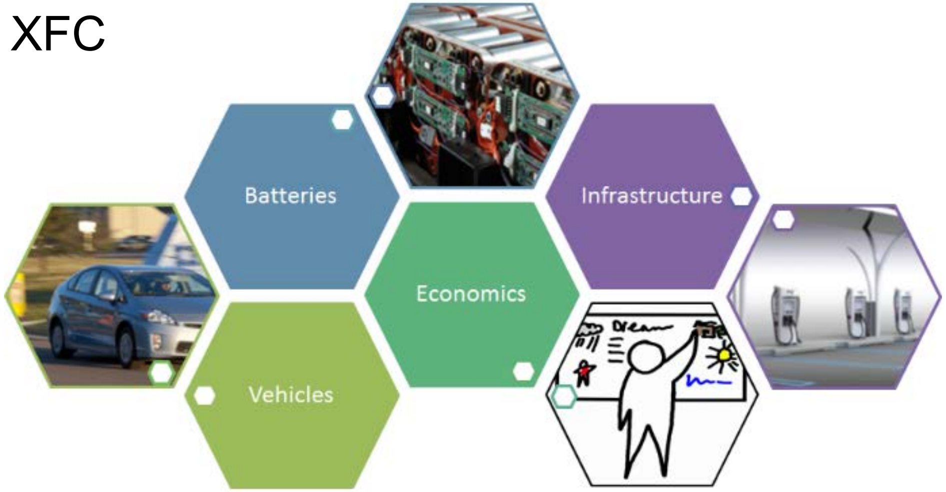
Partners

- U.S. DOE National Laboratories
  - Argonne National Laboratory (ANL), Idaho National Laboratory (INL), National Renewable Energy Laboratory (NREL)
- Industry Stakeholders
  - Automotive OEMs, Utilities, EVSE manufacturers & network operators, battery developers

Relevance

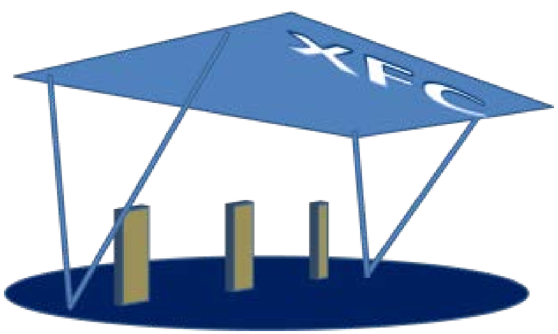
- **Objective:** Leverage National Lab expertise integrated with industry guidance and findings to produce a strategic document examining the technical gaps associated with extreme fast charging (XFC) of BEVs up to 400 kW
  - Battery, vehicle, infrastructure, and economic considerations are the primary focus areas
  - Define the R&D needs to enable XFC

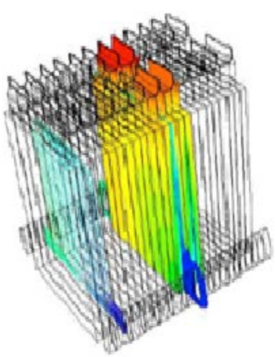
- **Impact:** Fast charge can help promote market penetration, alleviate the 'range anxiety' often cited by consumers as a barrier to adopting the technology, and improve the utility (or electric vehicle miles traveled - eVMT) of a BEV



Milestones

Fiscal Year	Date	Description	Status
2016	12/31/2015	Host industry stakeholder meeting at NREL to discuss direct current fast charge (DCFC) at 400 kW	Complete
2016	3/31/2016	Identify technology R&D needs for U.S. DOE to consider, from cell to infrastructure	Complete
2016	6/30/2016	Provide a written report to DOE Vehicle Technologies Office discussing XFC technology gaps	Complete



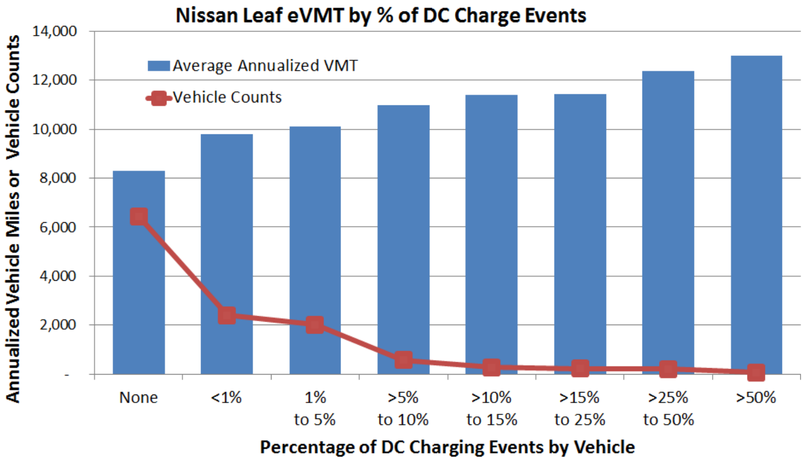


Approach

- **Stakeholder meeting:** engage industry on the topic of 400 kW extreme fast charging (XFC)
  - Identified barriers and opportunities for technology solutions needed to achieve 400 kW charging power levels
  - Capture industry perspective on the direction of fast charging
  - Used to guide and bound technology gap assessment report
- Collaboration among technology experts within the DOE National Lab complex
- Extensive literature review across battery, vehicle, and infrastructure areas
- Develop use-cases to assess the economic feasibility of XFC

Technical Accomplishments – Introduction

- DCFC Increases BEV Utility
  - Yearly electric vehicle miles (eVMT) traveled increases with use of 50 kW fast charging
  - Nearly 25% more miles driven annually when DCFC used for 1-5% of total charging events



	Level 1 (110V, 1.4kW)	Level 2 (220V, 7.2kW)	DC Fast Charger (480V, 50kW)	Tesla SuperCharger (480V, 140kW)	XFC (1000V, 400kW)
Range Per Minute of Charge (miles)	0.082	0.42	2.92	8.17	23.3
Time to Charge for 200 Miles (min)	2143	417	60	21.4	7.5

- EVSE Comparison
  - XFC should be able to charge a BEV in less than 10 minutes and provide approximately 200 additional miles of driving range

Source: McCarthy, Michael. "California ZEV Policy Update." SAE 2017 Government/Industry Meeting, Society of Automotive Engineers, 25 January 2017, Walter E. Washington Convention Center, Washington, DC. Conference Presentation.

Technical Accomplishments – Battery

- XFC Cost
  - BatPaC simulation comparing the effects of charging time on the required anode thickness, the heat generation in the pack and the resulting temperature rise, the pack cost, and the incremental cost of charging faster than 1-C (60 minutes) rate

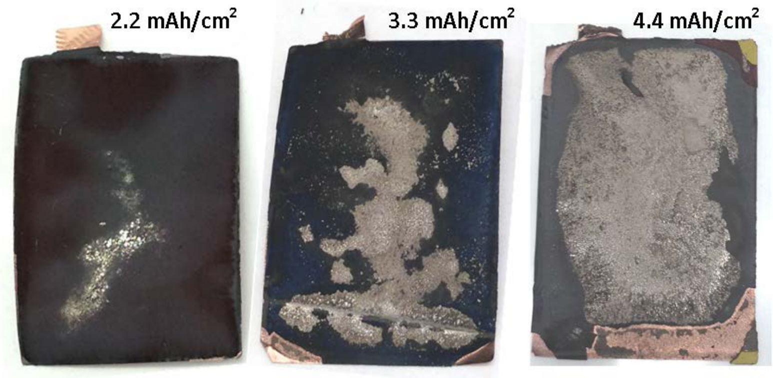
Charging Time, △SOC=80%, min	***8***	***10***	***23***	***47***	***53***	***61***
Charging Time, ΔSOC=60%, min	5	7	15	30	34	39
Charger Power Needed, kW	601	461	199	100	88	77
Anode Thickness, µm	**14**	**19**	**43**	**87**	**98**	**103**
Heat Generated during Charge, kWh per pack	2.35	2.20	1.89	1.77	1.75	1.45
Post-Charge Cell Temperature (ΔSOC=80%), °C	22.4	24.4	25.9	26.4	26.4	19.5
Cell Mass, kg	2.75	2.40	1.74	1.49	1.46	1.45
Cell Cost to OEM, $ per kWh	**$229**	**$196**	**$132**	**$107**	**$104**	**$103**
Cost Difference, $ per kWh	$126	$93	$30	$4	$1	$0

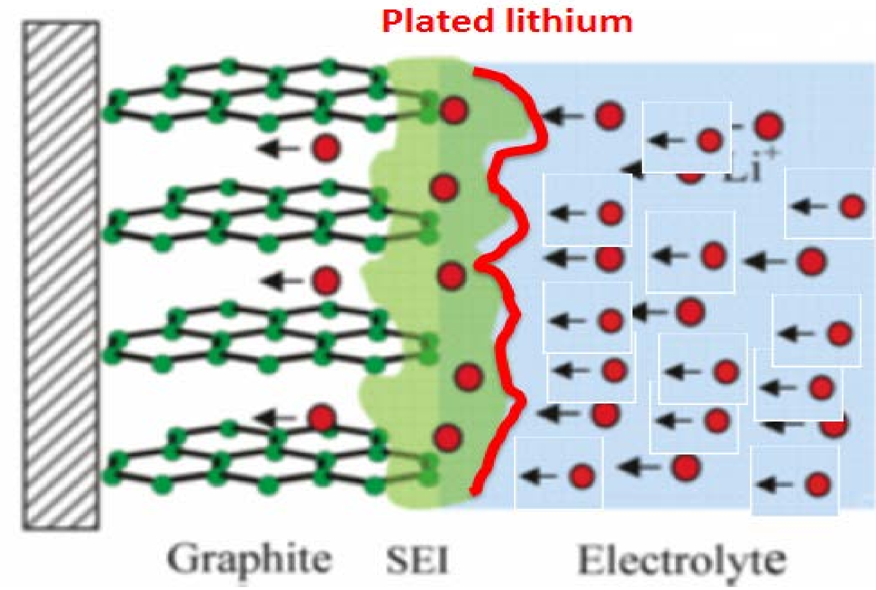
Cell Chemistry: NMC 622-Graphite; Pack Energy: 85 kWh; Rated Power (10 sec burst): 300 kW ; MACD (Maximum Allowable Current Density): 4 mA/cm^2; Number of cells per pack: 240

Thinner electrodes can facilitate high rate charging but increase cell cost

Technical Accomplishments – Battery

- Lithium Plating
  - Higher areal capacity (mA/cm^2) can increase the likelihood of plating



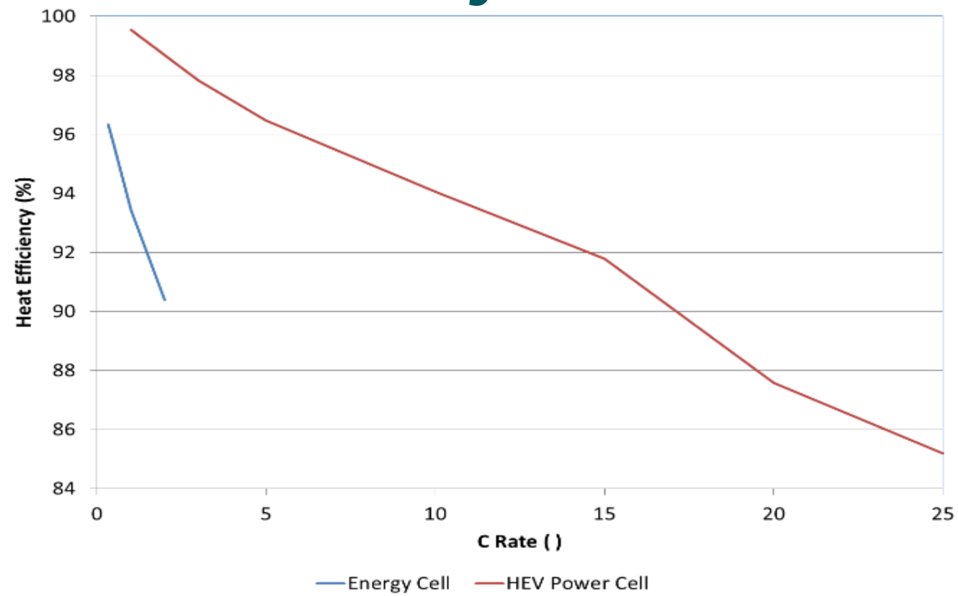


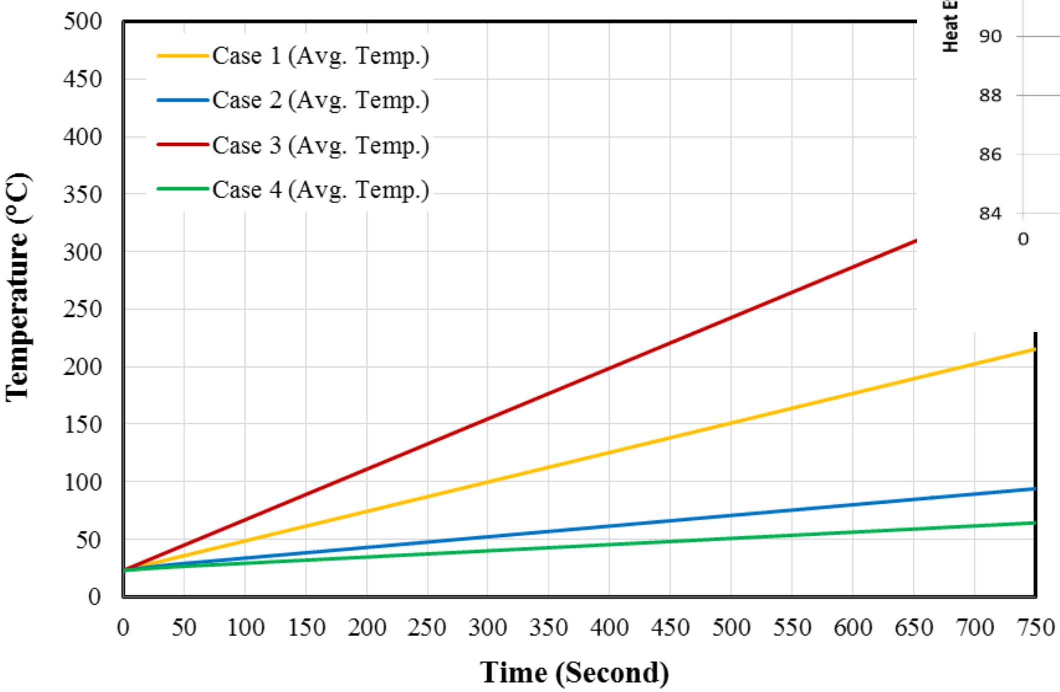
- Charging Rate
  - At extreme high charge rates, greater numbers of Li ions move to intercalate into graphite, but time and space constraints limit intercalations, so lithium ions may start plating as metal onto the surface of graphite

XFC can induce lithium plating and impact performance, life, and safety of a cell

Technical Accomplishments – Battery

- **XFC Thermal Considerations**





Case 1			Case 2		
Energy Density	175	Wh/kg	Energy Density	300	Wh/kg
Cell Efficiency	70	%	Cell Efficiency	90	%
Heat Removed	2	kW	Heat Removed	15	kW
Case 3			**Case 4**		
Energy Density	300	Wh/kg	Energy Density	175	Wh/kg
Cell Efficiency	70	%	Cell Efficiency	90	%
Heat Removed	2	kW	Heat Removed	15	kW

Cell design can limit C-rate and impact thermal efficiency, life, safety, and cost

Technical Accomplishments – Battery

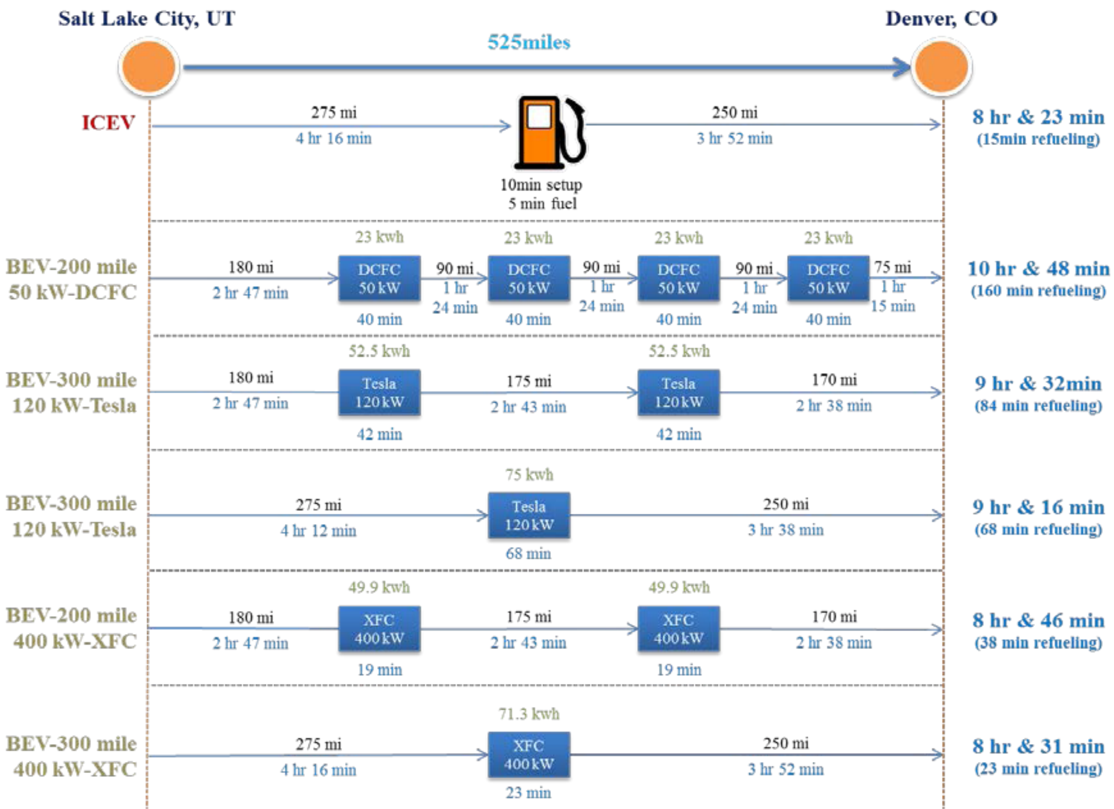
XFC Battery R&D Needs

- **Material & Cell Level R&D**
  - New anode materials to prevent or mitigate Li plating
  - New electrode designs to allow fast diffusion in and out of reaction sites
  - Study effects of XFC on state-of-the-art materials to gauge suitability and explore degradation mechanisms
  - Understand/detect/prevent Li plating in operation to remedy safety and performance issues
  - Abuse response of the cell due to XFC conditions may change and raise safety concerns

- **Pack Level R&D**
  - Improve thermal management
  - Higher pack voltages (up to 1000 V) may be needed to reduce cost and weight of battery – more series connections will require more sensors for monitoring and robust BMS systems for control/management
  - Advanced BMS to ensure cell balance after repeated XFC charges in order to minimize non-uniform aging and reductions in performance

Technical Accomplishments – Vehicle

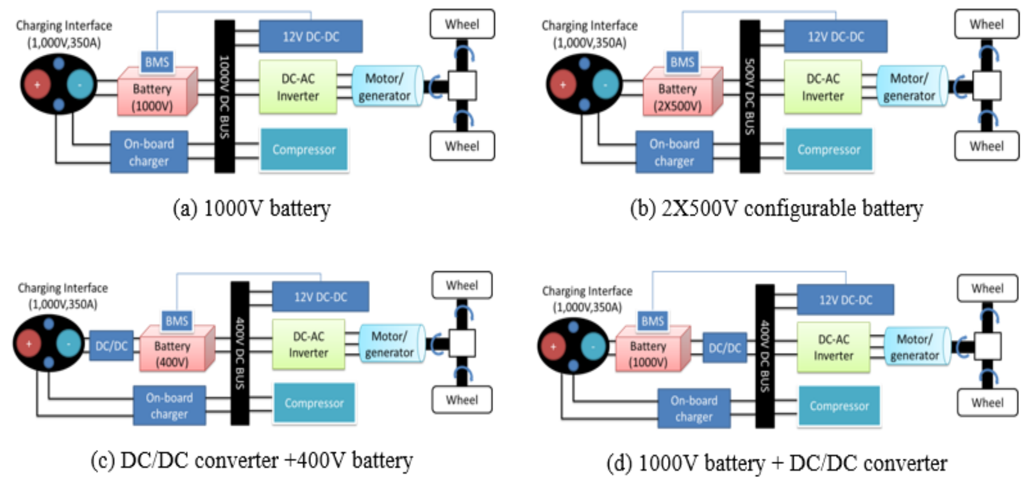
- BEV vs. ICEV
  - Hypothetical drive from Denver, CO to Salt Lake City, UT covering 525 miles was analyzed
  - Four different vehicle types.
  - Only an 8 minute difference in travel time between ICEV and the XFC enabled BEV with a 300 mile range battery.



XFC has the opportunity to place the BEV range and refueling experience in near parity with an ICEV

Technical Accomplishments – Vehicle

- Power Electronics
  - Higher voltage needed for XFC calls for different system architectures
  - Wide bandgap may be ideal for accommodating XFC voltage

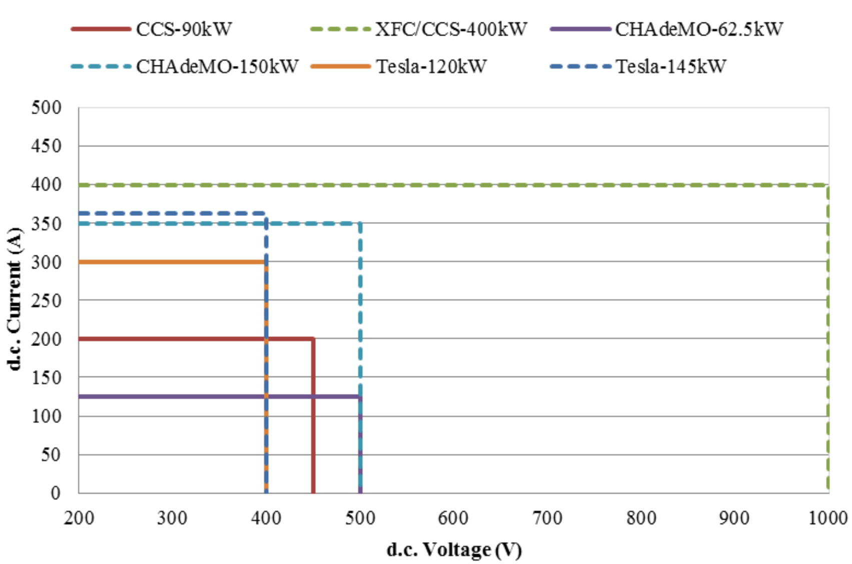


(a) 1000V battery

(b) 2X500V configurable battery

(c) DC/DC converter +400V battery

(d) 1000V battery + DC/DC converter



- Charging Connector
  - Unification among charging connector types will ensure a more robust XFC network
  - Charge connector should be compatible and interoperable across vehicle models and charging power capability

Technical Accomplishments – Vehicle

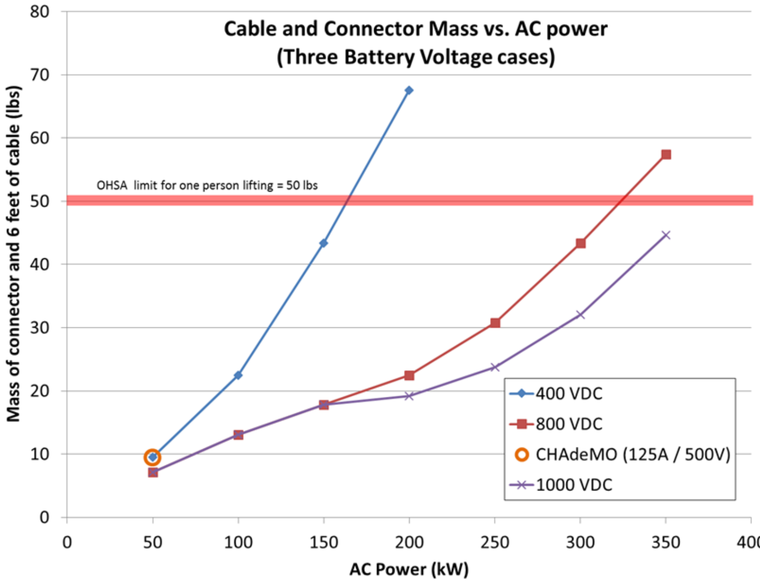
XFC Vehicle R&D Needs

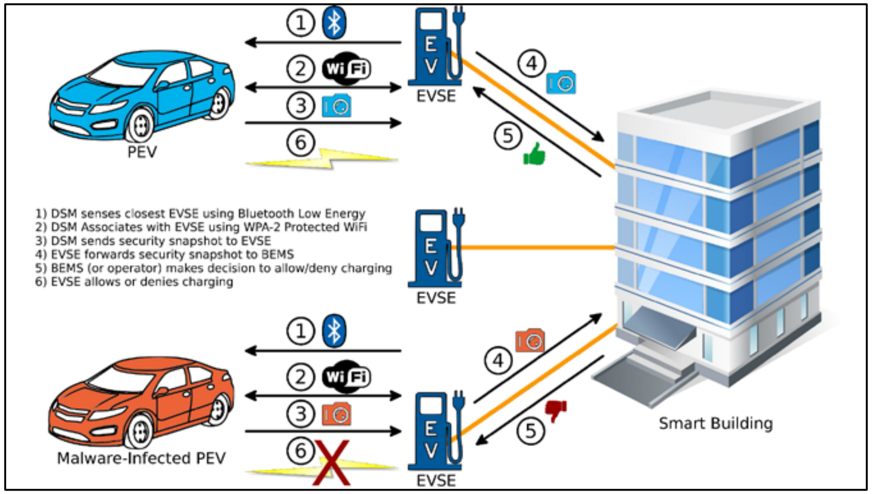
- **Power Electronics & Electrical Architecture**
  - Impact of higher battery pack voltages (beyond current 400V systems) on volume, weight, and cost for power electronics in XFC enabled BEVs
  - Electrical architecture design to accommodate XFC duty cycles
  - Automotive power electronic components capable of XFC power voltage levels
  - Motor design to include insulation, winding, and magnetic designs to account for higher system voltages

- **Interoperability**
  - Evaluations and testing of existing CCS connectors for XFC applications are needed to determine safe, reliable and robust operating limits
  - Standardization efforts are needed to ensure interoperability so that new and legacy vehicles are able to access XFC and existing DCFC networks
  - Cybersecurity research of vehicle/EVSE communications to ensure XFC and legacy vehicles can provide reliable transportation

Technical Accomplishments – Infrastructure

- EVSE & Charge Stations
  - Cooled cabling to handle XFC power while allowing user to easily plug-in
  - Unification of code & standards bodies (SAE, NEC)
  - Single backwards compatible connector for XFC EVSE

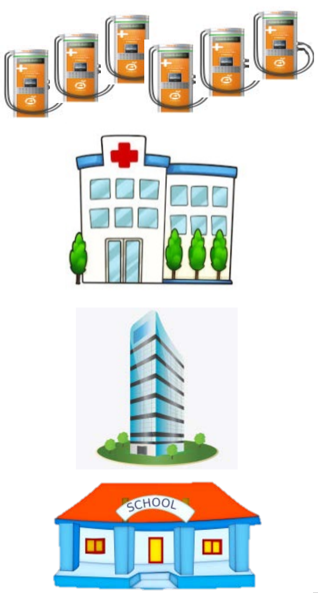


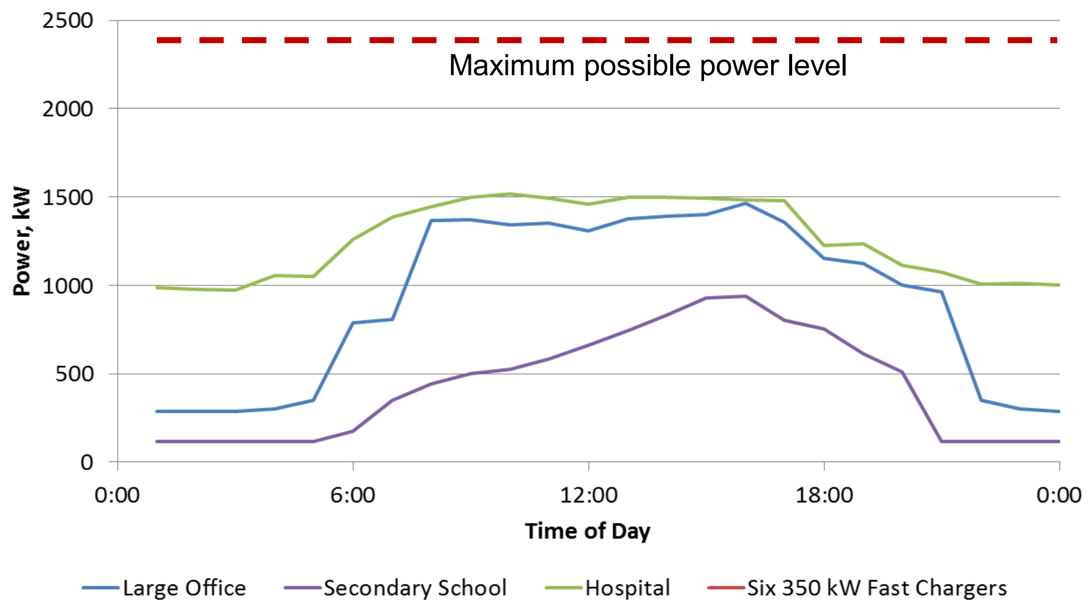


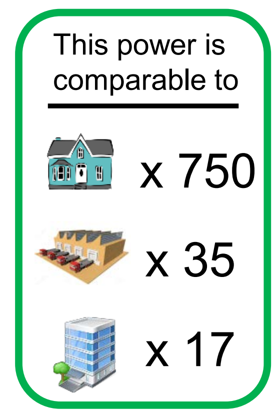
- Cybersecurity
  - All vehicles pose a cybersecurity risk
  - BEVs have additional vulnerabilities when connecting to the electric grid
  - XFC capable BEVs heighten cyber risk with the high power levels they draw
  - Securing BEV/EVSE communications and protocols crucial

Technical Accomplishments – Infrastructure

- Rate Structure & Demand Charges
  - Managing power and energy needs is crucial as demand charges can dominate operating costs of fast charge stations
  - Distributed Energy Resources (DER)







DER may help utilities cope with unpredictable/intermittent XFC power demands

NREL-developed load profile data for DOE commercial reference buildings in Baltimore area. From OpenEI.org.

Technical Accomplishments – Infrastructure

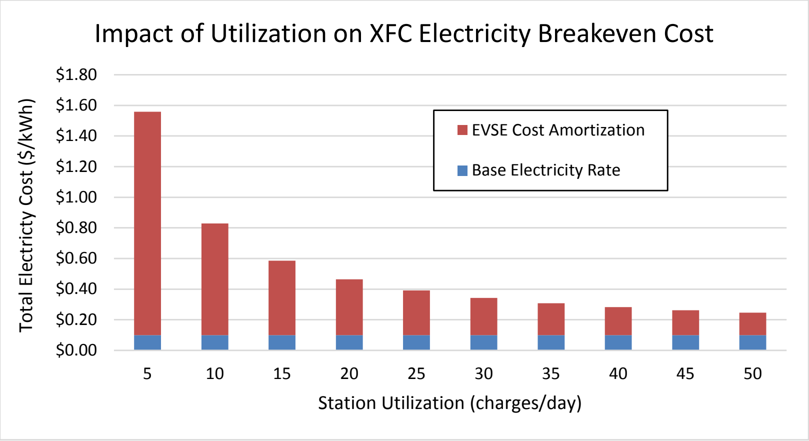
XFC Infrastructure R&D Needs

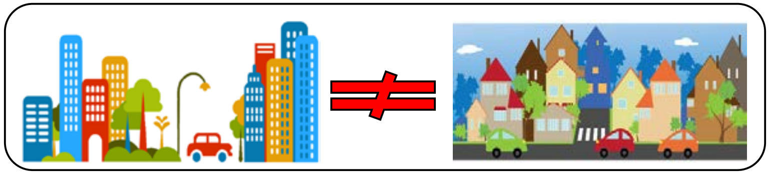
- **EVSE & Infrastructure**
  - Research technological improvements for advanced materials with better thermal and electrical properties to reduce and manage thermal loads in EVSE, in particular, the cable, but more materials research and equipment design engineering are needed.
  - Investigations into automated and even wireless EVSE for XFC applications
  - Challenges related to the Integration of on-site DERs

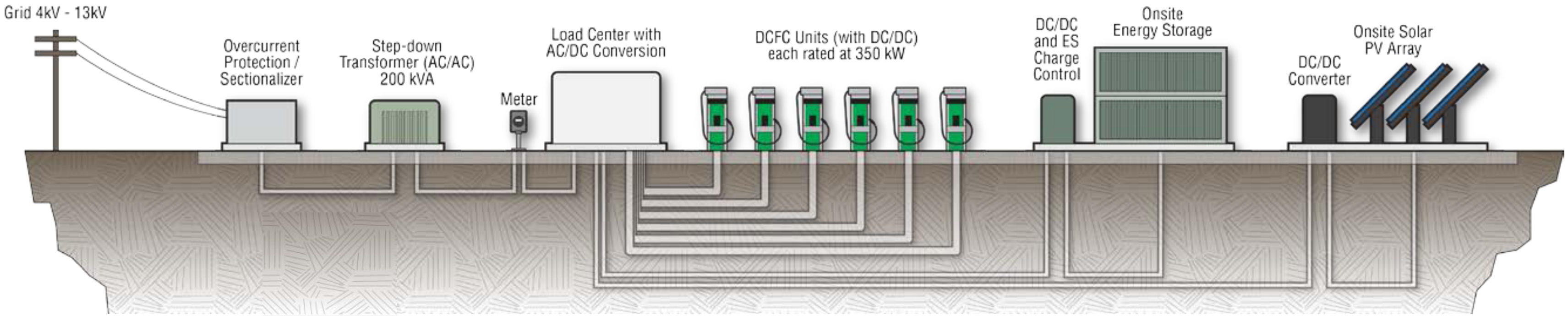
- **Industry**
  - Coordination and harmonization of permitting, siting and regulatory requirements to simplify XFC planning and deployment.
  - Unifying and harmonizing codes and standards, including applicability of liquid cooled cables, connector design, and cabling limitations.
  - Industry and AHJ engagement in standardization organizations such as SAE, NFPA, and others will be needed.

Technical Accomplishments – Economics

- XFC Use Cases
  - Fleets, ride-share, multi-unit-dwelling owners, private, commercial, CAVs
- Station Location & Citing
  - Citing stations in areas with high utilization and adequate utility service
  - Urban & Rural considerations
- Distributed Energy Resources (DER)
  - DER optimization







Source: McCarthy, Michael. "California ZEV Policy Update." SAE 2017 Government/Industry Meeting, Society of Automotive Engineers, 25 January 2017, Walter E. Washington Convention Center, Washington, DC. Conference Presentation.

Technical Accomplishments – Economics

XFC Economics Research Needs

- **XFC Stations**
  - Research to support effective coordination of corridor planning
  - Research to better understand the economic tradeoffs and operational benefits of on-site DERs and advanced technologies and management practices for operating distribution networks
  - Market research for effective utilization predictions in order to inform network build-out

- **Education & Outreach**
  - Education and outreach to both consumers and other stakeholders on the merits of vehicle electrification
  - Consumer and other stakeholder education and outreach on XFC and BEVs so they can make informed decisions. Education efforts will need to be tailored to the particular user segment and stakeholder group

Response to Previous Year Reviewers' Comments

- **This project was not reviewed at the 2016 Vehicle Technologies Office (VTO) Annual Merit Review (AMR)**

Collaboration & Coordination with Other Institutions

- **U.S. DOE National Laboratories**
  - Argonne National Laboratory[1], Idaho National Laboratory[2], National Renewable Energy Laboratory[3]
- **Industry Stakeholders**
  - Automotive OEMs: BMW, Daimler, FCA, Ford, GM, Nissan, Porsche
  - EVSE Manufacturers & Network Operators: ABB, AeroVironment, ChargePoint, Efacec USA, EVGO, GreenLots, Recargo/PlugShare
  - Battery Manufacturers: Farasis, JCI
  - Utility Suppliers: Black & Vaetch, BTC Power, EPRI, PG&E, Rocky Mountain Power, SMUD, SCE
- **Contributing Team**
  - Shabbir Ahmed[1], Ira Bloom[1], Andrew Burnham[1], Richard B. Carlson[2], Fernando Dias[2], Eric J. Dufek[2], Keith Hardy[1], Andrew N. Jansen[1], Matthew Keyser[3], Cory Kreuzer[3], Oibo Li[3], Anthony Markel[3], Andrew Meintz[3], Christopher J. Michelbacher[2], Manish Mohanpurkar[2], Paul A. Nelson[1], Ahmad Pesaran[3], David C. Robertson[1], Shriram Santhanagopalan[3], Don Scoffield[2], Matthew Shirk[2], Kandler Smith[3], Thomas Stephens[1], Tanvir Tanim[2], Ram Vijayagopal[1], Eric Wood[3], and Jiucai Zhang[3]

Proposed Future Research

- The technology gap assessment project is complete
- Future R&D programs and projects may leverage the findings of this report to guide and define desired portfolio outputs
- The gap assessment should be applicable to both government and industry funded research programs for entities located in the United States and Europe

Summary

Battery

- Cost, life, and performance for XFC cells pose significant technical challenges
- Research into new materials and electrode designs are needed to mitigate Li plating and thermal management constraints

Vehicle

- High voltage packs stand to impact vehicle cost, volume, and weight
- Electrical architecture and power electronics require further R&D
- Interoperability and standardization across XFC enabled vehicles is needed

Infrastructure

- EVSE charge delivery research
- Unification of codes & standards, permits, and regulatory requirements across industry
- Challenges with integration of on-site DERs for XFC complexes
- Power and energy management

Economics

- Utilization predictions and user group identification
- Corridor planning and coordination with other entities
- Understanding the benefits of on-site DER